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A Rapid Method for Screening Insecticides in the Laboratory

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Abstract: An efficient method for rapidly mass-screening insecticides for use against sap-feeding virus vectors is presented with a case study of 30 chemicals. The method permits large numbers of insecticides to be tested simultaneously and relatively inexpensively in a sequence of laboratory bioassays. The sequence is designed to find the most effective pesticide at the lowest concentration giving control without phytotoxicity. The system was derived to test candidate insecticides to control tomato yellow leaf curl virus vectored by the tobacco whitefly, *Bemisia tabaci* Gennad., the most serious pest of greenhouse and field tomatoes in the Middle East. Although the insecticides were all more efficacious in the laboratory than in the field, bioassay results were highly correlated with results from field trials, giving high confidence that the screening process selected only the most efficacious insecticides. Most of the insecticides accepted by the screening process have since been adopted by vegetable growers in Israel. The method is not intended to eliminate field efficacy trials, but to reduce the number of trials and treatments that need to be performed, thereby reducing costs.

The method provides for the optimization of application rates which will contribute to the expected life of insecticides before resistance develops, and will also help to reduce environmental contamination. In addition, the method is suitable for estimating relative efficacy for pesticide benefits assessments, a required part of the (re-)registration process for pesticides in some countries. Although developed for screening insecticides against virus-transmitting sap-feeding insects, the method could be modified to assess the efficacy of insecticides in controlling other insect pests.

Key words: *Bemisia tabaci*, tomato yellow leaf curl virus, greenhouse pest management, insecticide efficacy trials.

1 INTRODUCTION

The manufacturers of most pesticides understandably pay more attention to the half-dozen major crops than they do to the hundreds of minor crops, so the task of identifying potential chemical controls for the majority of crops falls to government, academic and extension scientists. With so many pesticides available, finding suitable efficacious chemicals for most minor crops can become a major undertaking. Field trials are the ultimate arbiter of pesticide efficacy, but a large comparative field experiment is expensive. It was against this background that we developed a procedure to streamline the screening of a large set of insecticides for use against whiteflies on primarily greenhouse-, but also field-grown, tomatoes. This paper presents the method that evolved during the course of the project, and a case study in which 30 potential chemicals were reduced in a series of laboratory bioassays to 10 for field testing.

Tomato yellow leaf curl virus (TYLCV) is the most serious cause of damage to the tomato crop in the Middle East. It is transmitted solely by the tobacco

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whitefly *Bemisia tabaci* Gennad.[1,2] Four hours of feeding by a viruliferous whitefly are sufficient to inoculate a healthy plant with a probability of 80%. The incubation period of the virus in the plant is two to three weeks.[1,3] TYLCV damage is inversely related to the age of the plant at infection: from the moment that virus symptoms appear, plant growth ceases and no further fruit are set.[4,5] The incidence of TYLCV-infected plants is directly correlated with the number of whiteflies trapped by yellow sticky traps, indicating the importance of whitefly dispersal in the epidemiology of TYLCV[3,6] (Berlinger, M. J. *et al.*, unpublished). During June–July the number of trapped whiteflies increases, reaching its peak in September with a corresponding increase in virus-infected plants. Thereafter both decrease towards winter.[5,6] During winter and spring whitefly activity is markedly reduced, with very few trapped and little evidence of TYLCV.

The virus cannot be controlled directly, nor can virus-infected tomato plants be cured. The only way to control TYLCV is to prevent its transmission by whiteflies. Control of whiteflies by biological, behavioral, and/or cultural methods is rarely effective enough to prevent probing and consequent virus transmission. Thus, keeping whitefly numbers low enough to eliminate virus transmission requires spraying them, sometimes as frequently as daily, during the first two or three months after planting.[5,7]

The intensive nature of spraying required to avert the virus,[6,8] the few insecticides labelled for whiteflies on tomatoes,[6] and the high risk of whiteflies becoming resistant to the insecticides[9–11] made it desirable to screen the large number of insecticides not already labelled. The need to screen many insecticides quickly, reliably, and at low cost indicated a laboratory bioassay that would provide comparable results from year to year. Obviously, the laboratory tests could only be a preliminary to field trials under commercial conditions. Thus the aim was to reduce the number of potential insecticides to a workable number for field testing, while ensuring that all candidates with the potential to control TYLCV spread in tomatoes were selected for field testing.

2 METHODS

The complete method for mass screening insecticides to control a virus vector was derived in three phases, the last being the field trial. The first phase focused on evidence of phytotoxicity, and the second on efficacy. An important component in all screening trials is the inclusion of a Standard Insecticide (SI) against which all candidates are tested. To begin with, the SI should be selected for its known or assumed efficacy. Subsequently, if the procedure is to become a regular program, the best-performing insecticide in one cycle will become the SI for the next. In addition to the SI, an untreated control is included to check the viability of the pest. The three phases of the procedure are summarized as a flow chart in Fig. 1.

2.1 Description of the procedure

In Phases 1 and 2, the performance of the candidate insecticides was assayed in a series of short bioassays. The objective of Phase 1 was to find the lowest concentration of insecticide which performed at least as well as the SI, without causing phytotoxicity. Phase 2 was a pair of bioassays performed three and six days following treatment of the plants that were designed to ensure that mortality was not a very short-term effect but was good for at least a week.

The selection of bioassay is fundamental to the success of the method. In the test case to be described in the following section the bioassay was of adult female whiteflies kept in close contact with treated tomato leaves using clip-on leaf cages. We have found this technique to be very effective, inexpensive, simple to use, and applicable in a variety of experimental situations. Four hours was sufficient time to obtain sufficient mortality for analysis in most cases. In the description which follows, this bioassay should be kept in mind.

2.1.1 Phase 1

Two greenhouse-grown potted tomato plants (*Lycopersicon esculentum* Mill.; determinate cultivar VF M-82-1-8; Hazera Company, Israel; at the four- to six-leaf stage) were treated by dipping for 10 s in each candidate insecticide solution. The solutions were initially at the concentration recommended on the label, but the method allowed for changes to the concentration. Twenty-four hours after dipping, clip-on leaf cages (modified Munger cell) were attached to three leaves per plant. Ten to twenty adult female whiteflies were collected with aspirators from rearing cages and introduced to each leaf cage. The whiteflies used in the bioassays were taken without regard to age, from laboratory cultures maintained in a semi-climatically controlled greenhouse at $25(\pm 5)$°C. To ensure that our whitefly cultures were as similar as possible to wild whiteflies, the cultures were started afresh each autumn from whiteflies collected in commercial cotton fields.

After 4 h of forced contact in a controlled environment chamber under continuous light at $27(\pm 1)$°C and 60% relative humidity, mortality was determined and scored as a percentage. Comparisons between the test insecticide and the SI were performed using the Student-Newman-Keul's test at $P < 0{\cdot}05$ for randomized blocks. For treatments with survival greater than the SI the bioassay was continued with the survivors for a further 20 h. After 24 h, survival was scored a second time. If survival still exceeded that of the SI, the chemi-

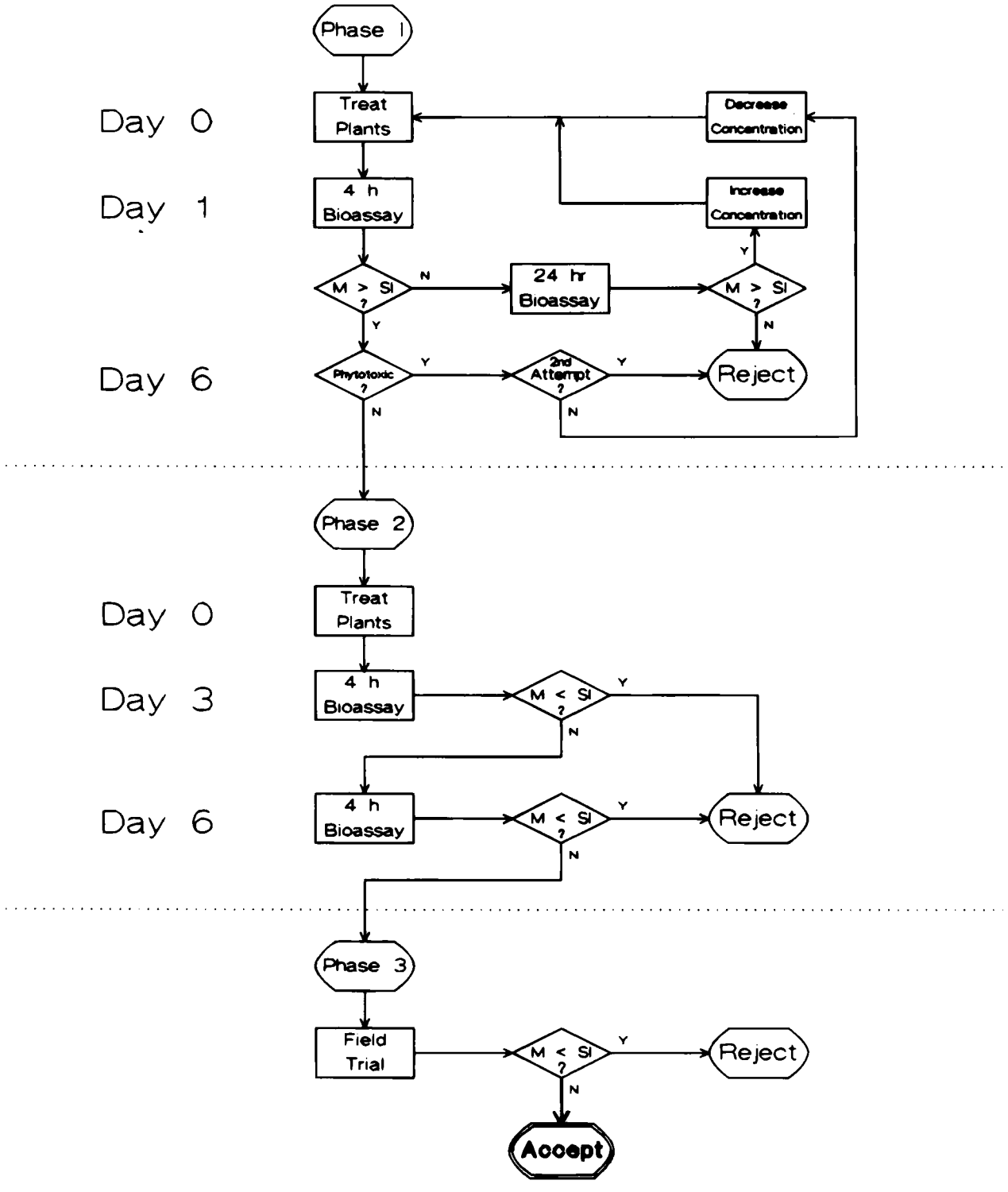

Fig. 1. Flowchart of the operations in the rapid mass screening of candidate insecticides to control TYLCV infection of tomatoes by *Bemisia tabaci*. The flowchart shows the sequence of bioassays and decisions made to select candidate insecticides for field trial. Key: SI, mortality obtained with the standard insecticide; M, mortality obtained with the candidate insecticide; Y, yes; N, No.

cal was rejected. If, however, the chemical was at least as effective as the SI, its concentration was increased, and the test restarted with new plants and insects.

If, after the first 4-h bioassay, mortality was at least as great as that of the SI, the plant was returned to the greenhouse to assess phytotoxicity. Treated plants were examined on the sixth day after the treatment for possible phytotoxic effects. Symptoms of phytotoxicity included yellow spots or wilting, especially of the younger leaves, and leaf shedding. If phytotoxic symptoms appeared, the insecticide was either eliminated from the trial, or its concentration was reduced and the

test restarted with new plants. If a chemical failed the phytotoxicity test after a reduction in concentration, it was rejected.

Chemicals failing to show symptoms of phytotoxicity and having 4-h bioassay mortalities at least as great as the SI were then tested in Phase 2. Phase 1 can be completed in as little as six days, but two weeks was typical for a test of more than 10 insecticides.

2.1.2 Phase 2

Because all chemicals reaching this point had already passed the test of Phase 1, the objective here was to find insecticides that would continue to perform at least as well as the SI for up to six days. Again, greenhouse-grown tomato plants at the four- to six-leaf stage were used for the bioassays. The bioassay method was the same as in Phase 1. Four-hour bioassays were conducted at three and six days following treatment; mortality was again recorded and compared to that for the SI. This stage took one week to complete; combined with Phase 1, the total time required to screen an insecticide was two to three weeks, and a batch of, say, 10 candidates took three to four weeks. Insecticides successfully completing both phases were then tested in a full-scale field trial in Phase 3.

2.2 Validation study

To validate the laboratory procedure, 10 insecticides were subjected to both the laboratory screening procedure and field testing. This validation study was conducted separately from the trials which are reported in the Case Study which follows. The insecticides used were chosen to cover a range of efficacies, and so were selected for the validation field trial after they had been laboratory screened. They are listed in Table 1, and appear again in Table 3 which reports the results of the trials used in the Case Study.

The field trial was conducted during August–October when the whitefly population normally peaks.[6] The trials were performed in 5 × 2 m plots, each containing 30 tomato plants, planted in three rows of 10 plants each. Every treatment, including the no-treatment control, was replicated six times in a randomized complete block design. In order to ensure, as far as possible, an equal probability of virus infection rate of all plants and to minimize edge-effects, each plot was bordered by a row of untreated tomato plants which had been inoculated previously in the laboratory with TYLCV.

Insecticides were applied twice a week, with a high-volume, high-pressure back-pack sprayer at the label rate unless a better rate had been selected by the screening procedure. The concentration of biphenate was reduced, cypermethrin ('Syprin'), cyhalothrin and cypermethrin + methidathion concentrations were increased over label rates (see Table 3). Efficacy was evaluated weekly by counting the plants that showed virus symptoms. The experiment was terminated when all six unsprayed control plots had reached 100% infection. Yellow sticky traps were used to monitor the whitefly population as a check to ensure a typical field population density.

Pearson's product moment correlation coefficient, r, was used to compare the mortality obtained in the

TABLE 1
Field and Laboratory Efficacy of Insecticides against Whitefly and Their Influence on TYLCV Spread in Tomatoes

Insecticide	*Laboratory test (%) mortality in bioassays after*			*Field test Virus-free plants (%) after 9 weeks*
	1 day	*3 days*	*6 days*	
'Virol' Mineral oil	50·0	36·0	12·0	0·0
Azinphos-ethyl	85·7	36·2	14·0	7·0
Cypermethrin ('Cymbush')	96·0	82·0	87·0	77·4
Cypermethrin ('Syprin')	96·0	96·0	85·0	80·9
Cypermethrin ('Titan')	96·0	82·0	77·0	77·4
Furathiocarb	97·0	60·4	0·0	7·0
Cyhalothrin	100·0	96·3	96·0	90·7
Cypermethrin + methidathion (1 + 1)	100·0	100·0	36·0	55·0
Fenpropathrin[a]	100·0	100·0	100·0	94·0
Biphenate[a]	100·0	100·0	91·0	94·0
Control	0·0	0·0	0·0	0·0
Pearson's r	0·66	0·90	0·98	

[a] Biphenate ('Talstar'®) was the SI at the time these bioassays were performed; fenpropathrin ('Smash'®) was subsequently used as the SI.

TABLE 2
Results of a Mass-Screening of 30 Insecticides against Whiteflies Carrying TYLCV on Greenhouse Tomatoes

Common name	*Formulation, concentration (g litre^{-1})*	*Trade name*	*Supplier*	*Final AI conc. (g litre^{-1})*	*Field test result*[a]
Pyrethroids					
Deltamethrin	EC, 250	Decis	Roussel Uclaf	3·0	
Flucythrinate	EC, 100	Cybolt	Cyanamid, Italy	5·0	
Cypermethrin	EC, 100	Cymbush	ICI	3·0	+
Cyhalothrin	EC, 50	Karate	ICI	3·0	+
Cypermethrin + methidathion	EC, 50 + 50	Phenopracide	Ciba-Geigy	3·0	−
Fenpropathrin	EC, 100	Smash	Sumitomo Chemicals	3·0	+
Fenpropathrin + mineral oil	EC, 100 + EC, 800	Smash + Virol	Sumitomo Chemicals Pazchem	3·0 + 10·0	+
Cypermethrin	EC, 200	Syprin	Dow Chemicals	1·5	+
Biphenate	EC, 100	Talstar	FMC Chemicals	1·5	+
Cypermethrin	EC, 200	Titan	Shell International	1·5	+
Organophosphates					
Azinphos-ethyl	EC, 200	Cotnion	Makhteshim Chemicals	10·0	
Dichlorvos	EC, 1000	Divipan	Makhteshim Chemicals	3·0	
Diazinon	EC, 250	Diazol	Makhteshim Chemicals	3·0	
Chlorpyrifos	EC, 480	Lorsban	Dow Chemicals	9·0	
Triazophos	EC, 300	Hostathion	Hoechst AG Verkauf	5·0	
Acephate	WP, 750[b]	Orthene	Landwirtschaft	3·0	
Fenitrothion	EC, 100	Nuvathion	Chevron Chemicals	3·0	
Parathion	EC, 500	Parathion	Cheminova A/S	5·0	
Chlorpyrifos-methyl	EC, 240	Reldan	Sandoz SPA	4·5	
Chlorpyrifos + dimethoate	EC, 240 + EC, 400	Lorsban + Rogor	Dow Chemicals Dow Chemicals	2·0	
Carbamates					
Furathiocarb	EC, 400	Deltanet	Ciba-Geigy	3·0	
Mecarbam	EC, 500	Murfotox	Dow Chemicals	7·0	
Organochlorides					
Chlorbenside	EC, 250	Benzilan	Makhteshim Chemicals	2·0	
Oils					
mineral oil	EC, 800	Virol	Pazchem	10·0	−
vegetable oil	EC, 900	Unnamed	Machteshim	10·0	
Others					
Amitraz	EC, 200	Amitraz	FBC	15·0	
Thiazopyr	WP, 480[b]	Pyridine K-840	Rhone Poulenc[c]	3·0	
thiocyclam-hydrogen oxalate 50 SP	SP, 500[b]	Evisect Nextar	Sandoz BASF	1·0 0·75	+
NI-25	EC, 200		Nissan	0·75	+
Acetamatirol	EC, 200	Opanuk	Mitani Toatsu	5·0	
Pyridaphenthion	EC, 400				

[a] Blank, chemical was not field tested; −, chemical was rejected; +, chemical was accepted.
[b] g kg^{-1}.
[c] Thiazopyr is supplied commercially by Monsanto under the trade name 'Visor'.

laboratory bioassays in Phase 1, Day 1, and Phase 2, Days 3 and 6 with the final percentage of plants not showing virus symptoms in the field plots. Each point in the correlation analysis was one chemical, thus the correlation was conducted on 10 bivariate pairs; the controls were not included in the analysis. The correlation between adult mortality (%), after 4 h of forced contact in the laboratory tests, and the proportion of virus-free plants in the field was the lowest on Day 1 ($r = 0{\cdot}66$), rising to $r = 0{\cdot}90$ on Day 3, and $r = 0{\cdot}98$ on Day 6 (Table 1). All three correlation coefficients are significant at $\alpha < 0{\cdot}05$.

Multiple regression of the field results on the results of all three bioassays accounted for >99% of the

TABLE 3
Examples of the Effect of Changes in Insecticide Concentration on Their Acceptability for Control of Whiteflies on Tomatoes

Insecticide	AI concentration (g litre^{-1})	Mortality after treatment (%)				Notes
		Phase 1		Phase 2		
		Day 1	+24 h	Day 3	Day 6	
Cypermethrin + methidathion (1 + 1)						
first test:	3·0	100			77	Phytotoxic, higher concentration
changed to:	2·0	100	—	100	36	no injury; rejected, not field tested
Mecarbam						
first test:	5·0	28	96	—	-	Less effective, higher concentration
changed to:	7·0	40	99	—	—	rejected, not field tested
Cypermethrin ('Syprin')						
first test:	0·50	45	95	—	-	Less effective, higher concentration
changed to:	1·50	96	—	96	85	rejected by field test
Cyhalothrin						
first test:	2·0	71	100	—	-	
changed to:	3·0	100	—	96	96	Accepted by field test
Biphenate[a]						
first test:	4·0	100	—	100	92	Very effective, lower concentration
changed to:						
1	2·5	100	-	100	88	
2	1·5	100	—	100	91	
3	0·25	100	—	100	73	Accepted by field test

[a] The SI at the time these bioassays were performed.

variance. Reducing the predictor variables in the regression model to just the first and second bioassays accounted for only 85% of the variance. Thus, the third bioassay on Day 6 was a crucial determinant of the reliability of the screening method. When the full procedure was followed, the method predicted, with a very high degree of reliability, the likely field performance of insecticides to combat *B. tabaci*-vectored TYLCV.

3 CASE STUDY RESULTS

Over a five-year period, more than 50 active ingredients (some represented by several different formulations) have been screened for control of whitefly-transmitted TYLCV as part of our on-going tomato pest management program. One screening, comprising 30 chemicals in three batches, is reported here as a case study of the laboratory screening procedure.

The results of the mass-screening experiment are presented in Table 2. In general, insecticides of the organophosphate, carbamate, organochlorine and the pyridine groups did not perform well compared to the SI (fenpropathin 100 g litre^{-1} EC; 'Smash'®). Most of the pyrethroids were efficacious in the laboratory test, and many proved effective in the field and were thereafter recommended for use.

Of the 30 chemicals screened, only one, cypermethrin + methidathion ('Phenopracide'), caused phytotoxicity at the recommended concentration. The concentration AI was reduced from 3 to 2 g litre^{-1} and retested: it was subsequently rejected in Phase 2 because the efficacy after six days was substantially below that of the SI (Table 3). Only one chemical tested was effective at a concentration lower than the recommendation: bifenthrin 100 g litre^{-1} EC ('Talstar') was screened several times at successively lower concentrations, and a reduction in concentration from 4 to 1.5 g AI litre^{-1} remained effective up to Day 6 (Table 3). A number of chemicals proved unsatisfactory at 4 h and were continued for 24 h. Of these, deltamethrin, acephate and fenitrothion, among others, were eliminated at the 24-h stage because they were still less effective than the SI. Two chemicals, cypermethrin ('Syprin') and cyhalothrin, both proved effective at a higher rate up to six days (Table 3). Several chemicals passed Phase 1, proving effective after one day, but were rejected on Day 3 or 6. 'Virol' mineral oil was found to be ineffective on all days, but was field-tested because it is widely used, often in combination with another product; on its own it failed the field test (Table 2). Chlorpyrifos-methyl 240 g litre^{-1} EC ('Reldan') was highly efficacious on Day 1, but rapidly lost efficacy over subsequent days, demonstrating the ability of this stepwise bioassay method to reject highly volatile and short half-life insecticides before an expensive field trial.

Of the 30 chemicals tested in the laboratory, nine (excluding 'Virol') were accepted for field testing by passing both Phases 1 and 2. Each batch completed Phases 1 and 2 in two weeks. A total of six weeks was required to screen all 30 insecticides. The subsequent field trial took 10 weeks, the results of which are given in Table 2.

4 DISCUSSION

The results of our validation experiment provide a high degree of confidence that the laboratory results are predictive of field results. The very high reliability of the method might come as surprise to some. Entomologists who conduct efficacy trials will have found, all too often, that rigorous laboratory methods designed to estimate acute toxicity do not always correlate well with mortality in the field. The problem is that field conditions do not always correlate well with laboratory conditions, and the vagaries of weather can play havoc with the dose transfer efficiency of a pesticide. Surprisingly, dipping plants in insecticides and confining insects on the plants for a fixed period simulates high-volume field-spraying very well. Clearly, this method could be further improved: spraying the plants instead of dipping them, and conducting the trials outside, subject to sunlight and weathering, are obvious elaborations, if needed.

Although the method was specifically derived to find suitable control(s) for a vector of a semi-persistent virus, the method is suitable for rapid laboratory screening of all sap-feeding insects by adjusting the duration of the bioassay. For example, a 24-h bioassay proved adequate to screen for suitable controls for *B. tabaci* on cotton.[12,13] The ease of detecting the virus contributed to the effectiveness of the method by simplifying and increasing the speed of laboratory–field validation experiments. The condition limiting the effectiveness of this method is the speed with which the bioassays can be performed. Provided a reliable bioassay can be developed, the general method should be easily adapted for most defoliating insects.

Previous methods for screening insecticides for whitefly control were better suited to the immature stage[13,14] or to direct damage to the crop[12,15–17] and thus did not serve our purpose in preventing the TYLCV spread. The insecticide screening methods we have tried included adult mortality after 4-h exposure one day after dipping, but the results did not correlate well with the field results (Table 1). Methods based on the virus incubation time were of high precision but required a relatively long time, more than three weeks, for each bioassay. Although the final recommendations must always be based on field results, we have found that our stepwise bioassay ensures that only the most promising insecticides are tested in the field.

An essential part of this method is the use of a standard insecticide (SI) against which all others are compared. The standard insecticide ensures selection of insecticides of equal or better efficacy, and the untreated control ensures the vitality of whiteflies on untreated plants. This method permits the option of increasing or decreasing the concentration of the candidate insecticides so as to obtain the minimum concentration necessary for control. The policy of comparing candidate pesticide efficacy against a standard ensures that variations in test conditions do not influence the decision to accept or reject. In general the SI will be the most efficacious chemical known and will be used commercially, but these are not absolute requirements. By making comparative assessments of efficacy, we can eliminate the inherent differences between efficacy trials, and maintain a continuity in comparisons, even as one chemical is superseded by another. The main advantage of the SI, however, is that statistical comparison is simple but rigorous.

In summary, the main advantages of our laboratory screening method are:

- laboratory tests are considerably less expensive than field trials,
- they are more easily controlled and analyzed,
- results are more repeatable than comparable field experiments,
- experiments can be conducted at any time of the year.

However, there are some disadvantages of the laboratory test. Setting up and checking the bioassays is time-consuming, and the timing of the bioassays is critical. The limiting factor is the number of experimental units (replicates × treatments) that one person can process. The observations require a high degree of accuracy, and need to be made quickly. Furthermore, a high proficiency is needed to distinguish the dead whiteflies from the living ones. We have found that the most consistent results are obtained when one person performs all the bioassays. Even though his/her assessments may not be unbiased, the effect of bias is effectively removed by comparing all results to the SI (which is always included in a batch for screening).

Although our screening method was not developed with the specific intention of reducing pesticide use, the method can be used to optimize the amount of pesticide applied. Furthermore, it may have broader applicability in the area of pesticide benefits assessment. It is ideally suited for obtaining efficacy data quickly. Labelling and re-labelling pesticides in the United States and many other countries, requires assessment of the human and environmental risks, the agricultural and economic benefits, and a risk-benefits analysis of the pesticide. The required data include pesticide use rates and areas,

commodity production and marketing costs, relative costs and performance of control measures, effective costs of worker exposure, costs to the environment, including endangered species, water quality, and other residue concerns, and costs of pesticide resistance management. Risk-benefits analysis is intended to integrate these widely different factors and examine the impact on them of a range of regulatory options available to government from full registration to outright cancellation. Between the extremes of the regulatory spectrum are the options that deal with labelling changes, classification, and use restrictions.

The results of the risk-benefits analyses that contribute greatly to the final decision are frequently based on incomplete data. Finding the data for a comprehensive pesticide benefits assessment is no simple matter.[18] The data required for benefits assessment include crop cost and production data, chemical label data, chemical use data and chemical efficacy data. The first three are relatively easy to acquire, but efficacy data are frequently very difficult to obtain. However, for benefits assessment it is more important to get a reliable ranking of the efficacy of control alternatives than to derive an absolute numerical value for the benefit of a treatment. Thus, efficacy data of pesticides expressed in relation to an SI is entirely suitable for a benefits assessment.

Concern over chemical crop protection is a challenge of increasing significance for agriculture. Pressure to reduce the quantity and toxicity of pesticides in use is likely to grow over the next few years, with the result that many of the pesticides growers have become accustomed to using will either be voluntarily withdrawn from use, or banned by government regulation. In general, producers use the pest-control measures that experience has told them most effectively ameliorate their pest problems. This may result in the use of 'hot' chemical controls, even when there are other less toxic treatments available. Any reduction in the quantity of pesticide required for reasonable pest control reduces the environmental and societal burden imposed by chemical pest control. Pesticides are themselves an increasingly costly resource which need to be conserved as much as possible. Hence, any means for optimizing the amount of pesticide applied should lead to a more rational, safer, and cost-effective use of pesticides. Specifically, reductions in the quantity of active ingredient applied per unit area contributes to a lessening of problems such as groundwater contamination, drift and toxic effects on non-target organisms, food residues, and applicator safety. Furthermore, we need to use pesticides wisely to reduce the risk of resistance. Ultimately all control strategies will be countered by evolutionary adaptation, but we need to extend the life span of the pesticides we have without increasing field contamination more than is required to save a crop. This requires careful selection of the pesticide dose to achieve the desired level of efficacy. Methods for finding effective control at minimal concentrations are badly needed as the pressure to curb pesticide use continues to increase.

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